P-NET AND SENSOR VALIDATION.

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Abstract. Given the availability of intelligent sensors performing internal diagnostics, and digital communications systems such as P-NET to communicate the results, in what form should sensor fault data be communicated? This paper outlines the SEVA approach to instrument validation (Henry and Clarke 1993), which advocates exploiting the manufacturer's knowledge of an instrument to detect faults internally, while describing the impact on each measurement in generic, device-independent terms (including the dynamic uncertainty). It is asserted that standard metrics for measurement data validity must be agreed, ideally as a supplement to the various fieldbus standardisation efforts.

Keywords. P-NET, FDI, Sensor Fault Detection, Uncertainty, Sensor Validation.

1. INTRODUCTION

The traditional approach to sensor fault detection has always assumed that the sensor is 'dumb' and can output only a single analogue measurement signal. Under these constraints the most common way of distinguish between a sensor fault and a genuine change in the process value is by building a process model, and comparing model behaviour with actual plant behaviour. A whole set of techniques known collectively as Fault Detection and Isolation (FDI - Patton 1994) have been developed to detect and diagnose sensor faults. However, it has proved difficult to apply these techniques to the process industries, due not least to the expense and inaccuracy of process modelling.

More recently, microprocessor technology has offered the possibility of embedding processing power within the sensor itself. This offers a number of advantages, not least self-diagnostics. Instead of observing the sensor's behaviour externally, and trying to distinguish sensor effects from process effects, internal signals or indeed active self-tests can be monitored for any indication of failure, exploiting to the full the instrument manufacturer's own expertise and knowledge of the instrument.

Already, many commercial digital sensors are providing simple diagnostics. However, under the 4-20mA regime, it is only possible to communicate a single channel of measurement data to the control system. A number of solutions have been found for communicating additional data over a twisted pair, but with the advent of industrial digital communication systems such as P-NET, standards are developing for two-way communication of complex data. Thus, for example, measurement and fault information may be communicated to the control system simultaneously.

Unfortunately, the various standards committees have had little opportunity to consider the sensor fault data formats. Typically, today's intelligent instrument generates a device-specific error code (e.g. fault 43 - damaged membrane) or a single good-bad validity bit. While the former may be adequate for maintenance, neither is particularly helpful for determining any necessary operational response to a sensor fault.

From an operational perspective, the key issue is what effect any sensor fault has on the quality of the measurement data. In general there will be a complex relationship between a sensor fault and the resulting measurement quality. If a single sensor generates multiple measurements, then each measurement may be affected differently by the occurrence of a single fault. Each sensor type may have dozens of potential fault modes, and there will be at least marginal differences between similar instruments from different vendors.

No user can relish the prospect of creating databases of operational responses to every possible sensor fault mode in a plant. A generic metric for measurement quality is thus required.

2. THE SEVA SCHEME

The SEVA approach to instrument validation (Henry and Clarke 1993) distinguishes between a sensor fault and the impact that the fault has upon the sensor's measurement(s). It advocates exploiting the manufacturer's knowledge of an instrument to detect faults internally, while describing the impact of each fault on each measurement in generic, device-independent terms (including the dynamic uncertainty).

The starting point for the SEVA sensor is the state-of-the-art intelligent instrument with an embedded microprocessor (performing measurement calculations and diagnostics) and an interface to a digital communications system such as P-NET (Henry and Wood 1992, Henry 1995a).

A SEVA sensor employs self-diagnostics, but provides extra stages of processing. If a fault occurs its impact on each measurement is assessed, and the measurement is corrected if necessary. Validity indices are generated which describe the resulting quality of each measurement in generic, device-independent terms. These enable the control system to make an appropriate response to the sensor fault irrespective of the particular sensor technology or supplier. This is of course not possible using device-specific error codes.

Figure 1 shows the parameters generated by the SEVA instrument. There are two validity indices generated for each validated measurement value or VMV (corresponding to the conventional measurement). These are called the Validated Uncertainty (VU) and the Measurement Value Status or MV Status. Additionally, a single Device Status is generated, which summarises the physical health of the sensor itself. Of course, a detailed, device-specific diagnosis of any fault is always available for the maintenance engineer.

2.1. Validated Uncertainty

Uncertainty is a well-established engineering concept. For any measurement x, the associated uncertainty, δ_x, expresses a reasonable bound for the measurement error, at a given level of probability. In other words, the true value of the measurand might be expected to lie within the uncertainty region surrounding the measurement, that is within $x \pm \delta_x$.

Uncertainty is defined and applied in numerous national and international standard documents (see for example ANSI 1985). In particular, it is used to quantify error when tracing the calibration of an individual instrument back to known reference standards. In custody transfer applications, for example, it is frequently a requirement that an instrument of known uncertainty (assuming strict limits on process behaviour and ambient conditions) is used to meter the process fluid.

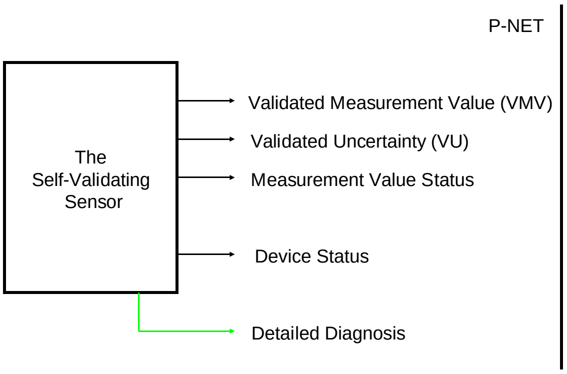

Fig. 1. Parameters generated by the Self-Validating Sensor

An uncertainty value takes into account a number of factors affecting the accuracy of the associated measurement, including measurement technology, calibration error, installation effects and environmental effects. Traditionally uncertainty has been a static analysis, assigning a constant uncertainty value to an instrument. In the SEVA scheme, the uncertainty of each measurement is calculated every sample, to allow for dynamic effects. Note that as the values are calculated in real time with changing process values, separation of uncertainty into bias and precision terms, as described in certain standards, is not appropriate. The definition of uncertainty is further extended to include the impact of any sensor faults on the measurement.

The standards provide a rule for calculating the uncertainty of arbitrary functions. Given the uncertainties of x and y, say, we can calculate the uncertainty of R, where R = f (x,y), using the following sum of squares formula:

$$\delta_R^2 = \left(\frac{\partial R}{\partial x}\right)^2 \delta_x^2 + \left(\frac{\partial R}{\partial y}\right)^2 \delta_y^2$$

For example, if x is volumetric flowrate, y is density, and R is mass flowrate, then R = xy, and the uncertainty in R is given by $\delta_R^2 = y^2\,\delta_x^2 + x^2\,\delta_y^2$. So, if vol. flowrate = 2.0 ± 0.04 litres/s, and density = 1000.0 ± 30kg/m^3, then the mass flowrate = 2.0 ± 0.072 kg/s. Note that the uncertainty of R depends not only upon the uncertainties of x and y, but will change dynamically with x and y themselves. Using this calculus it is possible to assess the uncertainty of any process or plant parameter which is inferred from sensor measurements.

The Validated Uncertainty provides the major indicator of the quality of the Validated Measurement Value. The VMV itself is a ‘best estimate’ of the current value of the measurand. Under normal conditions it is calculated using the latest data from the transducer, but this is not always the case. If a minor fault affects the sensor then a correction may be applied, and if a major fault occurs then the VMV may be calculated by projection from historical data. While the VU will increase to accommodate the reduced accuracy of such estimates, by itself it cannot indicate that the current VMV is, say, based on historical rather than live data. This information may be important to the control system, which would not wish to continue feedback control based only on historical data. A second, discrete, validity index is also generated with each VMV to inform the control system in effect ‘how this VMV was calculated’, and this parameter is called the Measurement Value Status.

2.2. Measurement Value Status

There are six possible values of the MV Status, corresponding to six different scenarios for how the VMV has been generated. The principal four values are named after a visual analogy:

- CLEAR indicates that there is no fault, and that the VMV has been calculated normally from the latest transducer data.
- BLURRED indicates that the measurement has been partially impaired by the presence of a sensor fault, and that a correction has been applied in the calculation of the VMV. The VU is increased appropriately to indicate the reduced accuracy of the estimate.
- BLIND indicates that a diagnosed fault has occurred which has a severe impact upon the measurement, and so the current VMV is projected from historical data, not live transducer data. A BLIND measurement should never be used for feedback control.
- DAZZLED is a temporary status used when transducer data is clearly erroneous, but there is insufficient internal evidence to confirm that a substantial fault has occurred. The current VMV is projected from historical data, but the expectation is that the internal diagnosis will soon be resolved and that the status will then switch to one of the other values. DAZZLED is used to deal with the occurrence of temporary but severe effects such as a spike. It would, for example, be undesirable for a control loop to be switched to manual in response to the controlled measurement turning BLIND and then, only a few seconds later, the measurements were to return to CLEAR.

The two additional states are as follows:

- SECURE indicates that the VMV has been generated from redundant transducers or sensors, all of which are in nominal condition. This status is useful in critical applications where the user needs the reassurance that even if one transducer or sensor fails, CLEAR data will still be available.

  It may be further divided into SECURE - COMMON, where the redundant sensors of of the same type, and therefore potentially at risk of common-mode failure, and SECURE - DIVERSE, where they are not.
- UNVALIDATED indicates that validation has not been in operation in the sensor which generated the measurement.

Note that it is not only sensor ‘faults’ which may have a detrimental impact upon a measurement. A self-test, for example, may for a short time have a partial or severe effect on the measurement. In such circumstances the strategies for calculating the VMV, VU and MV status are the same as if the underlying cause *were* a fault, for it is the quality of the measurements which matter to the control system, rather than the underlying cause of any degradation in quality.

2.3. Device Status

The Device Status is a generic, discrete value summarising the health of the sensor for maintenance purposes. Every sample one of the following values is generated:

- GOOD: the sensor is in nominal condition.
- TESTING: the sensor is performing diagnostic tests which may have caused any loss of measurement quality.
- SUSPECT: the sensor may have suffered an aberration; the condition has not yet been diagnosed.
- IMPAIRED: the sensor is suffering from a diagnosed fault which has a minor impact on performance, warranting a low priority maintenance call.
- BAD: the sensor is suffering from a diagnosed fault which has a major impact on performance, warranting a high priority maintenance call.
- CRITICAL: the sensor is in a potentially dangerous condition, requiring immediate attention.

It is stressed that that the (single) Device Status refers to the health of the *sensor*, whereas the MV Status refers to the quality of each (of one or more) *measurement*. Normally there will be some correlation between the Device Status and MV Status(es) - for example, if the principal measurement is BLURRED then the Device Status is likely to be IMPAIRED.

CRITICAL is used to indicate that the sensor is in a condition that may cause (or have caused) a hazard, such as a leak of the process fluid or a dangerous reagent, fire or explosion. This status refers only to hazards generated by the sensor itself, rather than by the process. Clearly not all types of sensor are capable of reaching a CRITICAL condition.

3. EXAMPLES OF SEVA DEVICES

A number of prototype SEVA devices have been developed at Oxford, mostly based upon commercial sensors developed by the Foxboro Company. These include temperature (Yang and Clarke, 1997), mass flow (Henry, 1994b) and dissolved oxygen sensors (Clarke and Fraher, 1996).

Dissolved oxygen (DOx) sensors are widely used in both industrial and environmental monitoring applications, particularly for indicating the levels of oxygen dissolved in river water. The most common type of sensor is based on the Clark cell, which is an electrochemical cell for generating an electric current by chemical means, i.e. by supplying electrons to, and taking them from, molecules and ions in solution.

One of the most important fault modes associated with a DOx sensor is fouling of the cell membrane. This is a frequent hazard in, for example, waste water treatment plants. As described by Clarke and Fraher (1996), the impact of this fault is to reduce the apparent dissolved oxygen level, as well as increase the time constant of the measurement. In a water treatment application, this could lead to an unnecessary increase in water oxygenation to compensate for the apparent lowering of DOx; the increase in time constant could lead to a control loop becoming unstable.

A SEVA prototype has been developed which can not only detect the presence of membrane fouling, but estimate its extent and provide a compensated measurement, as well as an estimate of the time constant of the measurement. Figure 1 illustrates how the SEVA sensor responds to the fault mode. Firstly, the dashed line shows the uncompensated measurement which, over the course of several hours, drops to a very low level. The compensated measurement, with corresponding uncertainty bounds, stays close to the true DO level, which is measured independently using a separate, un-fouled sensor. Once the fault is detected, the MV Status changes to Blurred to indicate that the measurement is being compensated for a fault. Note also that the uncertainty level increases as the compensation calculation is not as accurate as the normal measurement.

The implications of the SEVA strategy for both maintenance and control are obvious. The operator is informed that a fault has occurred, along with the quality of the compensated measurement. On the basis of this information together with the operational requirements of the plant, it is possible to judge whether maintenance must be carried out immediately, or whether it is possible to carry on operating the plant using the compensated measurement until regular or cheaper maintenance can be carried out, perhaps hours or days later.

Henry (1994b) discusses the use of SEVA metrics for other aspects of plant management.

4. P-NET AND SEVA

Martin Leahy (Leahy et al., 1997) describes how P-NET has been used to automate Oxford's flow laboratory, which is used for developing and testing SEVA prototype devices.

The first generation of prototype devices typically consisted of a PC hooked up to a transducer or indeed a commercial transmitter. The PC acted as the SEVA transmitter, carrying out measurement, fault detection and validation functionality. P-NET PC cards have been used to provide communication between such prototype devices and a central control computer.

However, such implementations are unweildy in a number of respects, and since 1993 the Engineering Science Department, together with the Computing Laboratory at Oxford University, have been developing a modular, prototyping platform - Valcard - based on Field Programmable Gate Arrays and a hardware compiler, Handel. The background to this work, as well as descriptions of a number of prototype systems built using this technology, are described by Henry (1995) and Henry *et al.* (1996).

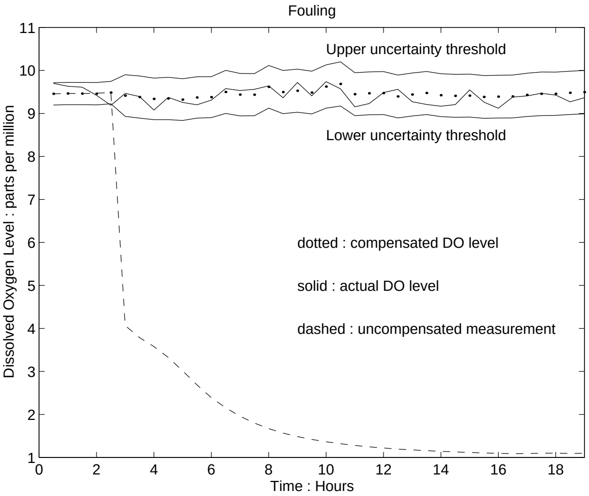

Fig. 1. Response of the SEVA DOx device to membrane fouling.

A new research project - Valcard II - funded by the UK Government, will continue the work by developing modules for communicating using a number of different standard protocols. In view of our experience with P-NET and its use for our laboratory automation, this will be one of the first protocols to be implemented. The intention is to allow the development of standalone prototypes for use in industrial trials and demonstrations of SEVA concepts.

It is hoped that such demonstrations will assist in the consideration of how best to convey sensor validity data over the various communication protocols, and that this in turn will lead on to the formation of new standards for data validity, to which the SEVA concepts will make a contribution.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

ANSI (1985). Measurement Uncertainty. ANSI/ASME PTC 19.1-1985.

Clarke, D. W, and P. M. Fraher (1996). ''Model-based Validation of a DOx Sensor''. Control Engineering

Practice, Vol. 4, No 9, pp 1313-1320.

Henry, M. P. and G. G. Wood (1992). The implications of digital communications on sensor validation. *IFAC Symposium on On-line Fault Detection and Supervision in the Chemical Process Industries*, Newark.

Henry, M. P. and D. W. Clarke (1993). The Self-Validating Sensor: Rationale, Definitions and Examples. *Control Engineering Practice*, 1, 585.

Henry, M. P. (1994a). A SEVA Sensor: the Coriolis Mass Flow Meter. *IFAC/IMACS Symposium, ''Safeprocess''*, Espoo, Finland.

Henry, M. P. (1994b). The Integration of Fault Detection within Plant-wide Data Quality Management. *IFAC/IMACS Safeprocess Symposium*, Espoo.

Henry, M. P. (1995a) Fieldbus and Sensor Validation. *IEE Computing and Control Journal.*

Henry, M. P. (1995b). Keynote Paper: Hardware Compilation - a New Technique for Rapid Prototyping of Digital Systems - Applied to Sensor Validation. *Control Engineering Practice*, July 1995.

Henry M. P., Archer N., Atia, M. R. A., Bowles, J., Clarke D. W., Fraher P. M. A., Page I., Randall, G, Yang J. C-Y. (1996). Programmable Hardware Architectures for Sensor Validation. *Control Engineering Practice*, October 1996.

Leahy, M.L., O. Maiuri, M. P. Henry and D. W. Clarke (1996). Sensor Validation and Fieldbus. 4th International P-NET Conference, Oporto, Portugal.

Patton, R. J. (1994). Robust Model-Based Fault Diagnosis: The State of the Art. *IFAC/IMACS Safeprocess Symposium*, Espoo.

Yang, J. C.-Y., and D. W. Clarke (1997). A Self-Validating Thermocouple. IEEE Transactions on Control Systems Technology, Vol 5, No 2, pp239-253.